

# Physical and combustion characteristics of pellet fuel from cotton gin by-products produced by select processing treatments

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## Abstract

Agricultural plant wastes when properly processed into useful commodities can become an economic asset. It has been estimated that over 2.04 million Mg of cotton by-products are generated each year in the United States. On average, disposal of these by-products costs the cotton gin approximately \$ 1.65 (U.S.) per Mg. One means of changing a financial liability into a potential revenue generator is to process the by-products into renewable, compact pellet-type fuel that can be used at the site or transported to the consumer. Furnace and water heaters that can burn pelletized plant materials have become popular and their safety, low pollution, and reasonable operational costs have been demonstrated. Also, the drastic increases in the price of liquified fuel and its uncertain supply place a premium for finding and using alternate, low-cost, cellulose-based fuels.

The objectives of our study were to fabricate pellet fuel from cotton gin by-products using select processing techniques, determine its physical properties, and measure the emissions when fired in a commercial pellet stove used for residential heating.

By-products from two cotton gins were collected and processed into fuel pellets. A total of seven different pellet fuels were evaluated, six from cotton gin by-products and one from wood. The treatments resulted from using different material streams from the ginning process as well as varying quantities of starch and/or crude cottonseed oil during the fuel pellet manufacturing process. The fuel pellet density from the various treatments ranged from 488 to 678 kg/m<sup>3</sup>. The various treatments were burned in a conventional pellet stove (four replications) and the gaseous and particulate emissions measured.

The average calorific value of the pellets ranged from 17.9 to 20.9 MJ/kg (HHV). The ash content for the various treatments ranged from a low of 4.88% to a high of 9.75%. The sodium content indicated concentration ranges from 91 to 282 ppm depending on the treatment.

The emissions from the cotton gin by-product pellets were higher than for a premium grade wood pellet. The emissions measured during testing were CO, NO, NO<sub>2</sub>, SO<sub>2</sub>, and particulates. The pellet stove was setup following the manufacturer's recommendation to burn wood pellets, but was not adjusted for the cotton gin fuel pellets.

By utilizing various additives and processing techniques, cotton gin by-products could be used to manufacture a pellet fuel that has commercial potential. However, work remains to minimize the ash content and determine the optimal settings for maximizing combustion.

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## 1. Introduction

Utilizing agricultural plant wastes/residues from harvesting or agricultural processing operations can be an effective means of turning currently unused biomass

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into useful commodities. One of the residues researched extensively over the last few decades has been the by-products from cotton gins also known as gin trash or gin waste (Thomasson, 1990). Over the years, research concerning the utilization of cotton gin by-products (CGB) has been performed to evaluate the usefulness and feasibility of this biomass for various applications including fire logs (Karpiscak et al., 1982), energy source (Beck and Clements, 1982; Lacewell et al., 1982; LePori et al., 1982; Parnell et al., 1991; White et al., 1996; Zabaniotou et al., 2000), livestock feed (Holloway et al., 1974; Conner and Richardson, 1987; Poore and Rogers, 1995), raw materials in asphalt roofing products (Kolarik and Smith, 1978), and compost (Hills, 1982; Shumack et al., 1991; Truhett, 1994; Tejada et al., 2001; Tejada and Gonzalez, 2003). About 2.04 million Mg of CGB are estimated to be generated each year across the cotton belt of the United States (Holt et al., 2000). Assuming as little as 34 kg of by-products are generated from each bale of cotton produced worldwide and using an average production of 94.9 million bales from 1999 to 2004 (Cotton Incorporated, 2005), the quantity of CGB that could be generated would be 3.23 million Mg. Despite extensive research efforts and the potential volume generated each year, very few uses for CGB ever developed into widespread commercial acceptance. Some of the more successful applications involve using CGB as a portion of the feed ration for livestock in feed yards (non-dairy), bedding for dairies, and in producing compost (Holt et al., 2000). Today, much of the available CGB is still disposed of by returning it back to the originating cropland. These applications, while successful in various localized situations, utilize only a small portion of the available CGB.

One of the obstacles often mentioned in the literature regarding a more complete utilization of CGB is the issue of “cleanliness”. CGB by its inherent nature contains varying amounts of particulate soil materials depending on the crop’s geographical location, method of harvest, and other factors. The approach for cleaning/screening the CGB, to remove the particulates in an effort to enhance its value has been emphasized throughout the literature (Young and Griffith, 1976; Kolarik et al., 1978; Axe et al., 1982). The most opportune place to remove the particulates is in the pre-cleaning stages at the cotton gin (Kolarik et al., 1978). However, a common practice at most cotton gins is to combine all the waste product generated, from the various pieces of equipment in the ginning process for storage at a central location. Holt et al. (2000) evaluated various properties associated with CGB generated from various equipment streams in the ginning process. Results indicated differences

associated with numerous properties depending on the processing equipment generating the by-products.

Based on problems encountered in the studies previously referenced, it was determined that a process, which adds value to the CGB to enhance commercial use of this biomass, would be beneficial. Such a process was developed at the United States Department of Agriculture, Agricultural Research Service (USDA-ARS), Cotton Production and Processing Research Unit’s facility in Lubbock, Texas. The procedure, known as the COBY Process (Holt and Laird, 2002), was originally designed for the purpose of adding value to CGB in the development of livestock feed and mulch, and further expanded for making fuel pellet. To date, various products produced from the COBY Process have been evaluated for their performance as an ingredient in livestock feed (Holt et al., 2003a) and mulch (Holt et al., 2003c, 2004a). An economic study concerning the manufacturing and distribution of fuel pellets produced by the COBY Process was also undertaken (Holt et al., 2003b, 2004b).

The objectives of this study were two-fold. First, to fabricate fuel pellets from the COBY Process utilizing different processing techniques/ingredients and to determine the physical properties of the pellets produced. Second, to evaluate the gaseous and particulate emissions derived from the prepared pellets using a commercially available pellet stove designed for residential heating and to compare such results with emissions from conventional premium grade wood pellets. The intent of the second objective was to see how the CGB fuel pellets would perform when they were burned in a residential type pellet stove that had been set up to burn wood pellets, but without any adjustments to the airflow or fuel feed rate.

## 2. Materials and methods

### 2.1. Materials

The wood pellets used in this study were purchased from one of the vendors listed on The Pellet Fuels Institute’s website (PFI, 2005). The CGB used came from USDA-ARS cotton ginning laboratories in Stoneville, Mississippi and Lubbock, Texas. The CGB from Mississippi contained all the waste streams from the ginning operation with the exception of the lint cleaner waste (i.e., motes). The Texas CGB contained only the waste stream from the Extractors (i.e., stick and bur machines). Material from the Extractors contains mostly sticks and burs with very little lint (less than 1% by weight). All the CGB were processed using the COBY Process

at the USDA-ARS, Cotton Production and Processing Research Unit in Lubbock, TX.

The two sources of CGB were used in conjunction with other ingredients to produce six different fuel pellet treatments. The names and ingredients used for the six different CGB treatments were: (1) Lbk 4, CGB from Lubbock with 4% added corn starch; (2) Lbk 10, CGB from Lubbock with 10% added corn starch; (3) Lbk 55, CGB from Lubbock with 5% added corn starch and 5% crude cottonseed oil; (4) Miss 4, CGB from Stoneville with 4% added corn starch; (5) Miss 10, CGB from Stoneville with 10% added corn starch; (6) Miss 55, CGB from Stoneville with 5% added corn starch and 5% crude cottonseed oil. The seventh treatment was a premium grade wood pellet purchased from a local vendor.

## 2.2. Equipment and pellet processing

A schematic of the process used to produce the CGB fuel pellets used in this study is shown in Fig. 1. The raw material was loaded using pneumatic conveying into a live-bottom bulk feed bin with five 22.9-cm augers. Upon exiting the feed bin, the gin by-products were sprayed with a gelatinized cornstarch solution. The starch in the

COBY process is added in an effort to reduce abrasion on the processing equipment resulting from the raw material. The sprayed material was conveyed, in twin cut-and-fold mixing augers, to a side-feeder that forced the by-product slurry mix into an Insta-Pro model 2000 extruder (Insta-Pro International, Des Moines, IA). The product exiting the extruder was conveyed to a belt drier where it was dried using 135 °C air. Upon exiting the drier, the material was cooled and stored in totes. Due to the number of treatments and the quantity of material produced for each treatment, the product was not pelleted using the gin labs CPM Master pellet mill, but was processed at a commercial animal feed manufacturing facility near Lubbock, Texas using a CPM 7000 series Pellet Mill (California Pellet Mill, Crawfordsville, Indiana). At the commercial facility, the raw material was force fed into the pellet mill where the product was pelleted into 2.5 cm long pellets, 0.64 cm in diameter. As the material was being fed into the pellet mill, water was added to help the material flow through the pellet mill and help form the pellets. The desired range of the moisture content of the material entering the pellet mill was from 15 to 20%. Upon exiting the pellet mill, the material fed onto a belt cooler, to a shaker table that removed fines, to a bucket elevator, to a finished pellet bin, and then

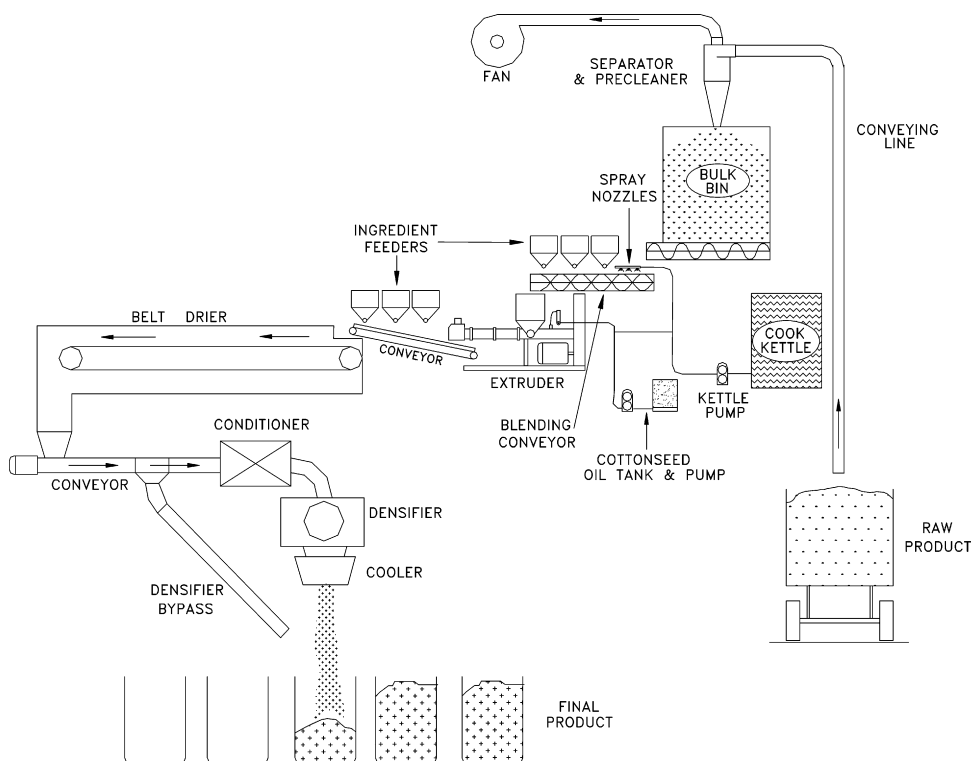


Fig. 1. Schematic of the equipment used in the COBY process to produce the six cotton gin by-product fuel pellets evaluated in this study.

bagged for storage. Each bag contained approximately 18 kg of pellets.

The gelatinized starch slurry consisted of 0.453 kg of starch to every 3.78 L of water in the cook tank. The starch slurry was applied at a consistent rate via a piston pump driven by a direct current (dc) motor regulated by a closed-loop control system. The control system consisted of a flow meter with a 0–10 VDC output signal to the dc drive regulating the speed of the motor driving the starch pump. The amount of gelatinized starch added to the by-products was 4 or 5% by weight of the raw material depending on the treatment. In the case of the 4% add-on, the amount of starch added for a bulk bin feed rate of 6.79 kg/min of by-products would be 0.34 kg/min. For the 10% starch treatments, 5% was added in gelatinized form and the remainder was applied through the dry ingredient feeders. The 5% corn starch and 5% crude cottonseed oil treatments were produced by applying 4% gelatinized starch, 1% dry starch, and 5% crude cottonseed oil. The cottonseed oil was injected into the starch line and applied through the starch spray nozzles. Water was injected as needed into the extruder barrel during processing. The rationale for adding various portions of the starch in a dry form was to help control the moisture content of the material exiting the extruder. The excess moisture is utilized by the dry starch and heat in the extruder causing the dry starch to gelatinize in the extruder barrel.

Feed rate from the bulk feed bin was determined from a mathematical relationship established before producing the pellets. A dc motor and drive was used to regulate the output from the bulk feed bin. The dc motor powered the feed bin augers through a 64–1 gear and sprocket reducer. Before processing the mulch, the raw material was loaded into the bulk feed bin and emptied at four different drive settings into a collection bin placed on a scale. The amount of material emptied during 15 min of operation was recorded for each of the four settings. This procedure was repeated three times for each setting to develop the mathematical formula necessary to determine the raw material output of the bulk feed bin at various intermediate settings of the dc drive. Temperatures of the extruder were recorded from two type-K thermocouples placed within the thermocouple wells located on the extruder barrel. The desired temperature range of the material exiting the extruder was 104–116 °C.

Even though the extruder was not specifically needed in the manufacturing of fuel pellets, it was used to help condition and mix the CGB and ingredients prior to pelletization. It should be noted that the extruder is beneficial for improving digestibility (livestock feed) and

sterilizing weed seeds (mulch), but is actually a hindrance for the production of fuel pellets. Ideally, to achieve maximum production rate, the material would be ground prior to the addition of starch and other ingredients and go through a mixer, conditioner, and into the pellet mill and forego the extruder altogether.

### *2.3. Material preparation, sample identification, and analytical analyses*

Once all the treatments had been manufactured, 500 g-samples were collected and sent to two different laboratories for analyses. One of the laboratories was randomly selected from the list on the Pellet Fuels Institute website (PFI, 2005), hereafter referred to as Lab A. The other laboratory selected was one that the research unit had used previously on various occasions, hereafter referred to as Lab B. In an effort to eliminate any possible bias, each sample was labeled with a numeric code instead of names. Each lab was sent two samples, with different numeric labels for the same pellets. Overall, a total of four measurements were made for moisture, ash, total sulfur, calorific value, and water-soluble sodium. In accordance with the recommendations on the PFI's website, measurements were also made for bulk density, fines, pellet diameter, and pellet length by Lab A. Additional procedures were performed by Lab B for proximate and ultimate analyses.

### *2.4. Pellet stove burn tests*

The stove burn testing involved the use of a Quadra-Fire Classic Bay 1200 pellet stove (Hearth & Home Technologies, Lakeville, Minnesota). The stove was installed in one of the laboratories at the USDA-ARS, Cotton Production and Processing Research Unit in Lubbock, Texas. A schematic of the testing setup is shown in Fig. 2. The stove was set up and adjusted to burn premium grade wood pellets following the manufacturer's specifications. For each test, the stove's fuel supply hopper was loaded with 2.5 kg of pellets. The stove was activated and allowed to operate until the convection blower was activated, but not less than 15 min before starting the run and initiating the data acquisition and emission measurement systems. The delay was necessary so that the pellet stove would be operating under "normal" conditions while the emissions were being measured. The Quadra-Fire stove has an exhaust and convection fan with adjustable speeds. For testing, both fans were set on "high".

After the startup period, the data acquisition and emissions measurement systems were activated and

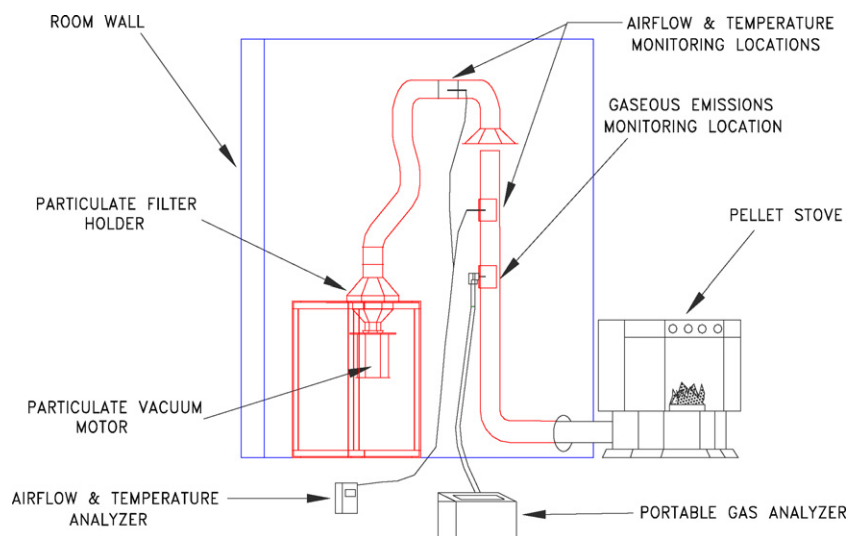


Fig. 2. Schematic of the test setup used to measure gaseous and particulate emissions from a commercially available pellet stove used for residential heating.

the testing began. Each test was performed for 20 min. The data acquisition system recorded the following data every 10 s: room temperature, outside temperature, barometric pressure, convection blower airflow, convection blower air temperature, exhaust blower airflow, exhaust blower air temperature, firepot temperature, ash bin temperature, start time of warm up period, convection blower start time, date, and end time of test run. The gaseous emissions of carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), nitrogen oxide (NO), nitrogen dioxide (NO<sub>2</sub>), sulfur dioxide (SO<sub>2</sub>), and oxygen (O<sub>2</sub>) were measured using an ECOM A-Plus portable gas analyzer (ECOM America, Ltd., Gainesville, GA). The various air flow and temperature readings taken were measured using the Kurz Series 2440 Thermal Anemometers (Kurz Instruments, Inc., Monterey, CA).

Before the actual emission measurements, the gas analyzer was checked for proper zero, calibration error, sampling system bias, and zero/span drift using certified calibration gases that covered the range of emissions measured. The calibration gases used for the analyzer were certified gases that were within 2% of the manufacturers tag value. The testing was conducted using Chapter Seven of the Test Q/A Plan for Verification of Portable NO/NO<sub>2</sub> Emission Analyzers document (ETVP, 1998) and the Environmental Protection Agency (EPA) Reference Method 6C (U.S. EPA, 1997a) as guidance documents.

Particulate emissions were measured using a variant of EPA Reference Method 5G (U.S. EPA, 1997b). The main variation from the method was the exclusion of the sampling train. As shown in Fig. 2, the particulates in the

pellet stove exhaust were collected on a glass fiber filter. The dilution tunnel aspect of Method 5G was utilized in an effort to reduce the temperature of the air being pulled through the vacuum motor. The vacuum motor pulled the stove exhaust through the filter media. Before testing, a trial run of each pellet fuel was performed to refine the sampling process. One of the main items that needed to be determined before testing was the duration of a run before the particulate filter media became loaded with particulate to the point of restricting the dilution tunnel airflow below the pellet stove exhaust airflow. The pellet stove exhaust averaged 0.877 standard m<sup>3</sup>/min with a standard deviation of 0.024. The trial runs revealed a safe maximum time of 20 min.

The dilution tunnel hood was not placed over the stoves exhaust until after the startup period. Similarly, the dilution tunnel sampling fan was not activated until the hood was in place. Immediately upon reaching 20 min of run time, the sampling fan was turned off and the dilution tunnel hood removed from the exhaust stack. The 20.3 cm × 25.4 cm glass fiber filters were placed in a desiccant cabinet for 36 h before being weighed. After each test run, the particulate filter was once again desiccated for 36 h before obtaining the final weight. The difference in filter weights was the particulate emissions for that test. The filters were weighed using an Ohaus Explorer Pro balance (Ohaus Corporation, Pine Brook, NJ).

Upon completing a test run, the fuel supply to the fire pot was shutoff and the stove allowed to cycle down (i.e., turn off the convection blower) following the manufacturer's timeframe programmed into the stove's elec-



tronics. During the period when the stove was allowed to cool, the particulate filter was recovered and the data acquisition file checked for any data logging errors. After the stove had cycled down, all unburned fuel in the pellet supply hopper and screw was removed and weighed. The difference in initial and final fuel weights constituted the quantity of fuel burned during the run. In addition to weighing the unused fuel, the ash was also collected and weighed. Once the stove had been cleaned out and all pertinent data recorded, the next fuel to be tested was placed into the stoves supply hopper and the process repeated.

### 2.5. *Experimental design and analysis*

The pellet stove burn testing was setup and analyzed as a randomized block design with day being the blocking factor. The treatments tested were: (1) Lbk 4, (2) Lbk 10, (3) Lbk 55, (4) Miss 4, (5) Miss 10, (6) Miss 55, and (7) Wood. Each treatment was replicated four times for a total of 28 runs. Standard analysis of variance techniques was used to analyze the data to determine statistically significant differences among the seven treatments by the Ryan-Einot-Gaberiel-Welsch Multiple Range Test (SAS Help, 2003) at the 95% confidence level.

## 3. Results and discussion

### 3.1. *Analytical results*

The analytical results are listed in Tables 1 and 2. The analytical data shows calorific value to be higher for Lbk 55 and Miss 55 than for any of the other fuel pellets due to the addition of crude cottonseed oil to these two treatments. Even though the Lbk 55 and Miss 55 pellets had the highest calorific values, they had the lowest bulk densities. The Pellet Fuel Institute specifies that pellets should have densities of  $640.7 \text{ kg/m}^3$ . Both of the fuel pellet treatments with cottonseed oil were below the specified density. One of the theories for the low densities was due to the addition of oil at the same percentage as the starch. The starch acted as a binder for the CGB; however, the oil acted as a lubricant and restricted the adhesive properties of the starch. Thus, because the starch and oil were added at equal percentages, the benefit gained from the cottonseed oil in calorific value was negated by the lubricity of the oil in terms of manufacturing a durable high density pellet. Another theory is the lubricity of the oil resulted in less resistance in the die, thereby limiting the ability of the pellet mill to densify the material as in the other treatments. An indicator of the durability of pellet produced can be seen in the fines

column in Table 1. Both the Lbk 55 and Miss 55 pellets produced greater fines than any of the other pellets during the quality analysis. The PFI standard is 1% fines. In retrospect, the ratio of starch to oil should have at least been around 2 (i.e., twice as much binder as oil).

Other properties listed in Table 1 are the ash, sulfur, water-soluble sodium, and pellet length. The ash content is significantly higher in all of the CGB pellets than the premium grade wood pellet. Even though the overall CGB fuel pellet ash content is two to three times lower than the ash content traditionally associated with “gin waste” (Domalski et al., 1986; Jenkins, 1993), it is still large enough to be a factor in pellet stoves that are not built to handle “high” ash fuel. In addition to the high ash content in the CGB pellets, both the sulfur and water-soluble sodium contents were higher than the wood pellets.

Even though the sodium contents for the CGB fuel pellets were not higher than the PFI’s specification of 300 ppm for a premium grade fuel pellet (PFI, 2005), the variability between treatments was surprising. Upon further investigation, it was discovered that the order in which the pellets were manufactured was: Lbk 4, Miss 4, Miss 10, Miss 55, Lbk 10, and Lbk 55, which is the descending order of the sodium content in the fuel. The water in the Lubbock area has sodium levels in the 40–50 ppm range. Because Lbk 4 was the first pellet produced, the amount of water injected into the extruder barrel to regulate the electrical load on the motor during processing was higher than it was for any other fuel. The rationale for using more water is more a function of the learning curve associated with manufacturing a fuel pellet using a new process than it is the fuel itself. Similarly, because Miss 4 was a different biomass compared with the Lubbock, Texas gin waste (i.e., more lint and less sticks and burs), the addition of water was greater than it was for the other treatments. After processing the Miss 4 treatment, the amount of water added to the process was minimal, if any. However, when the processed unpelleted CGB treatments were taken to a commercial facility for pelleting, the pellet mill operator was accustomed to pelletizing cottonseed meal and various dry grasses, and thus, followed his normal procedure of using excess water. Even though the operator was cautioned that this material would pelletize easier than the materials he was processing due to the addition of starch, the mistake of using excess water was still made. The CGB processed material was pelletized in the same order in which it was processed. By the time the Lbk 10 treatment was being processed, the amount of water added was essentially zero. This situation encountered due to the addition of water during processing, illustrates how

Table 1

Mean property values of the seven fuel pellet treatments evaluated in this study

Treatment	Bulk density <sup>a</sup> (kg/m <sup>3</sup> )	Calorific value <sup>a</sup> (MJ/kg)	Ash <sup>a</sup> (%)	Total sulfur <sup>a</sup> (%)	Water-soluble sodium <sup>a</sup> (ppm)	Maximum pellet length (cm)	Fines (%)
Lbk 4	641.6	18.41	5.58	0.235	282.0	3.05	1.1
Lbk 10	676.8	18.29	5.22	0.165	116.0	3.81	1.0
Lbk 55	534.9	20.81	4.88	0.185	90.9	2.54	3.5
Miss 4	607.8	17.97	9.75	0.345	250.0	3.81	0.4
Miss 10	677.8	17.90	8.17	0.310	210.0	3.81	1.0
Miss 55	488.1	20.93	7.72	0.260	195.0	3.81	2.2
Wood	655.7	19.72	0.49	0.025	58.8	4.45	1.0
Test method <sup>b</sup>							
E873	D5865	D1102	D4239	E776	PFI	PFI	

<sup>a</sup> Reported values are on a dry basis.<sup>b</sup> PFI: analytical methods specified on Pellet Fuel Institute's website. All other methods are ASTM (American Society for Testing and Materials) procedures.

important auxiliary inputs can be when manufacturing a new product.

The C, H, N, and O<sub>2</sub> values from the ultimate analysis are listed in Table 2. The sulfur and ash values are shown in Table 1. Similarly, the fixed carbon and volatiles from the proximate analysis are listed in Table 2. Overall, the wood pellets had a higher percentage of fixed carbon than the other fuel pellet treatments. The values shown in both Tables 1 and 2 illustrate the standard that a premium grade wood pellet sets for other biomass materials, such as CGB, when they are being used as a fuel source in residential pellet stoves.

### 3.2. Pellet stove emission testing results

The gaseous and particulate emission results from the pellet stove burn tests are shown in Table 3. Overall, the burning of wood pellets produced either significant or numerically lower particulates, CO, SO<sub>2</sub>, or NO<sub>x</sub> (NO

plus NO<sub>2</sub>) than any of the other pellets. As can be seen from Table 3 and Figs. 3 and 4, the CGB fuel pellets were not fired under optimal conditions/settings. The CO value in Table 3 illustrates the poor air-to-fuel ratio used in regards to the CGB fuel pellets. The hottest firepot temperature was obtained when firing the wood pellets. The average feed rate (kg/h) for each fuel is shown in Fig. 4. Because the feed from the pellet holding hopper was timed and not based on firepot temperature, and also because the stove was not adjusted during the testing, we do not know the reason why the Lbk 4 pellets had a higher feed rate than all the other treatments (Fig. 4). The Lbk 4 fuel had a higher density and a shorter length than the wood pellets, but so did Lbk 10 and Miss 4 and they did not feed as well as Lbk 4. Thus, the question arose, “were the pellets with densities greater than 640 kg/m<sup>3</sup>, too short?” Did the length of the wood pellets help the fuel entangle other pellets, and thus feed more effectively in this particular stove, compared with

Table 2

Additional characteristics of the seven fuel pellet treatments evaluated in this study

Treatment	Carbon <sup>a</sup> (%)	Hydrogen (%)	Nitrogen (%)	Oxygen (%)	Moisture <sup>b</sup> (%)	Volatile (%)	Fixed carbon (%)
Lbk 4	48.05	5.69	1.07	39.47	10.67	46.89	47.65
Lbk 10	48.16	5.51	1.22	39.97	8.25	47.00	48.05
Lbk 55	51.96	6.25	1.11	35.78	7.82	46.09	49.19
Miss 4	45.30	5.13	1.83	37.76	9.85	47.59	42.80
Miss 10	46.77	5.56	1.68	37.58	9.73	47.17	44.74
Miss 55	51.21	6.27	1.48	32.84	9.68	46.54	45.56
Wood	51.09	5.97	0.17	42.17	5.22	43.85	55.59
Test method <sup>c</sup>							
D5373	D5373	D5373	Diff	D5142	D5142	D5142	

<sup>a</sup> Reported values are on a dry basis for C, H, N, O<sub>2</sub>, volatile, and fixed carbon.<sup>b</sup> Moistures represent the moisture of the fuel pellets at the time of their arrival to the lab.<sup>c</sup> All methods are ASTM (American Society for Testing and Materials) procedures. The percent oxygen was determined by difference for the Ultimate analysis.

Table 3

Mean gaseous and particulate emissions from burning the seven fuel pellet treatments in a commercial pellet stove used for residential heating

Treatment	Average measured air pollutant emissions <sup>a</sup>						
	O <sub>2</sub> (%)	CO <sub>2</sub> (%)	PM (g/MJ)	CO (g/MJ)	NO (g/MJ)	NO <sub>2</sub> (g/MJ)	SO <sub>2</sub> (g/MJ)
LBK 4	18.24 a	2.68 b	2.34 a	13.66 a	1.21 ab	0.014 a	0.398 a
LBK 10	17.89 ab	3.04 ab	2.17 ab	10.18 a	1.20 ab	0.013 a	0.263 ab
LBK 55	16.92 ab	3.97 ab	1.74 bc	11.67 a	1.77 a	0.005 a	0.385 a
MISS 4	17.54 ab	3.36 ab	2.17 ab	9.25 a	1.83 a	0.014 a	0.304 a
MISS 10	18.26 a	2.65 b	1.84 abc	12.62 a	2.18 a	0.000 a	0.399 a
MISS 55	18.37 a	2.55 b	1.62 c	10.95 a	2.04 a	0.009 a	0.319 a
Wood	16.43 b	4.45 a	0.44 d	1.14 b	0.51 b	0.000 a	0.070 b

<sup>a</sup> Column means followed by different letters are statistically different at the 0.05 level of significance. O<sub>2</sub>: oxygen, CO<sub>2</sub>: carbon dioxide, PM: particulate matter, CO: carbon monoxide, NO: nitrogen oxide, NO<sub>2</sub>: nitrogen dioxide, and SO<sub>2</sub>: sulfur dioxide.

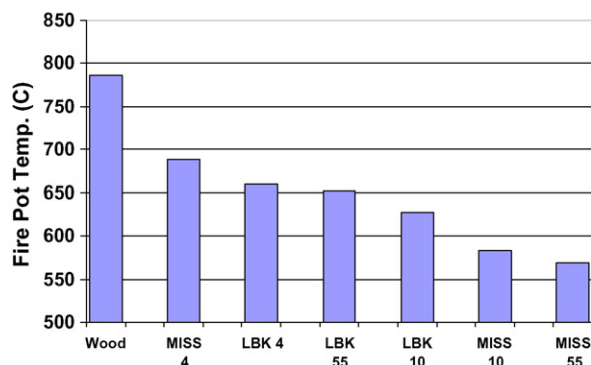


Fig. 3. Average firepot temperatures obtained during the burn testing for the wood and six cotton gin by-product fuel pellets evaluated in this study.

the other fuel pellets? One item that was not measured is the smoothness of the pellet exterior, referred to here as “slickness”. The Lbk 4 pellets were not as “slick” as the Lbk 10, Miss 10, and wood fuels. Thus, even though Lbk 4 had a shorter length and higher density than the wood pellets, the exterior roughness of the pellets may have contributed to more of the Lbk 4 pellets passing through the stove’s feed auger and into the firepot.

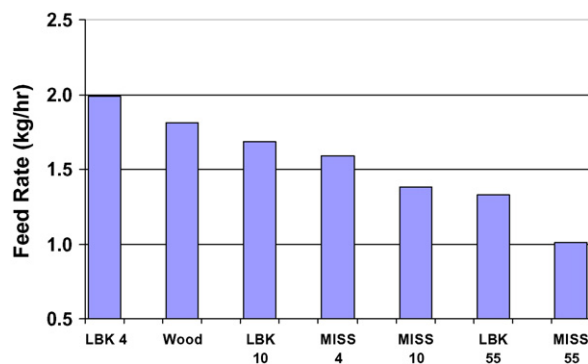


Fig. 4. Average feed rate (kg/h) obtained during the burn testing of the seven fuel pellets evaluated in this study.

The fact that the emissions is higher for the CGB fuels than for the wood pellet is not surprising considering the stove was setup to burn wood without any adjustments for the other fuels with different burning characteristics. One item of interest was the extent to which the emissions exceeded those of the wood pellet. According to Moran et al. (2004), the critical factors for optimum burn are pellet feeding rate coupled with the correct amount of air. In this study, neither of these factors was regulated to optimize the burn rate. Similarly, even though the pellets were uniform in diameter, there appeared to be enough variability among the treatments in at least one property (Table 1) to influence the fuels performance during testing.

#### 4. Summary and conclusions

This study was undertaken to address two primary questions: (1) can industry standard type fuel pellets be produced out of cotton gin by-products (CGB) utilizing a new processing technology, the COBY Process; (2) when fuel pellets made from this process are burned in a conventional pellet stove used for residential heating without making any modifications to the stove, how would the gaseous and particulate emissions compare with emissions that would be generated from firing a premium grade wood pellet? The results revealed that depending on the ingredients used and the method of manufacturing, a dense and durable fuel pellet could be produced from cotton CGB. However, when the fuel is burned in a commercial pellet stove without taking into consideration the air-to-fuel ratio necessary for change in fuel type, the gaseous and particulate emissions for all CGB fuel pellets exceeded those of the premium grade wood pellet used in this study.

Overall, CGB fuel pellets can potentially be a viable resource as a fuel. However, work remains in determin-



ing the optimal burner settings necessary to minimize emissions and maximize performance. Also, the high ash content of the CGB fuel currently restricts its use for residential applications because the user would have to monitor the firepot and routinely empty it for the stove to work for any length of time. Even though this fuel can be economically produced (Holt et al., 2003b, 2004b), it would not be prudent to produce the CGB fuel for consumer use until the ash can be reduced within reasonable limits, the ingredients and processing of the fuel determined and refined to the point of producing a consistent product, and the settings for optimal combustion are understood. It would be ideal if a pellet stove had the ability for the user to specify whether they were using wood fuel pellets or some other biomass, and adjust the air-to-fuel ratio accordingly.

This is a report on a work in progress, now that the initial study has revealed some areas needing improvement, future studies will focus on two areas of interest: (1) assisting stove manufacturer's in modifying or developing a stove to accommodate biomass fuel pellets that have differing fuel properties from conventional wood pellets, and (2) refining the process to minimize the ash content of the fuel and to develop a fuel, utilizing cotton gin by-products, which are more user-friendly for the existing pellet stoves currently available in the marketplace. In regards to refining the process, we have started blending CGB with guayule waste to make fuel pellets that overcome some of the problems encountered with CGB alone, such as lower ash content and higher energy value (Nakayama et al., 2003). Further efforts to blend other waste biomass resources of traditional crops (rice, wheat straw, and corn stalks) instead of depending on only one appear to be promising.

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## References

- Axe, D., Addis, D., Clark, J., Dunbar, J., Garrett, W., Hinman, N., Zinn, R., 1982. Feeding value of cleaned and uncleaned cotton gin trash. *Proc. Annual Meeting Am. Soc. Anim. Sci. Western Sect., Am. Soc. Anim. Sci.* 3, 57–59.
- Beck, S.R., Clements, L.D., 1982. Ethanol production from cotton gin trash. In: *Proceedings of the Symposium Cotton Gin Trash Utilization Alternatives*, National Science Foundation, pp. 163–181.
- Cotton, Incorporated, 2005. World cotton production, in: U.S. Cotton Market Monthly Economic Letter. February 11. Website: <http://www.cottoninc.com/MarketInformation/MonthlyEconomicLetter/>.
- Conner, M.C., Richardson, C.R., 1987. Utilization of cotton plant residues by ruminants. *J. Anim. Sci.* 65 (4), 1131–1138.
- Domalski, E.S., Jobe, T.L., Milne, T.A., 1986. *Thermodynamic Data for Biomass Conversion and Waste Incineration*, SERI/SP-271-2839. Solar Energy Research Institute and National Bureau of Standards, September.
- Environmental Technology Verification Program, 1998. *Test/QA Plan for Verification of Portable NO/NO<sub>2</sub> Emission Analyzers*. Batelle, Columbus, OH, pp. 28–38.
- Hills, D.J., 1982. Composting gin trash in California. In: *Proceedings of the Symposium Cotton Gin Trash Utilization Alternatives*, National Science Foundation, pp. 63–86.
- Holloway, J.W., Anderson, J.M., Pund, W.A., Robbins, W.D., Rogers, R.W., 1974. Feeding gin trash to beef cattle. *Bull. Mississippi Ag. Exp. Stn.* 818.
- Holt, G.A., Barker, G.L., Baker, R.V., Brashears, A.D., 2000. Characterization of cotton gin byproducts produced by various machinery groups used in the ginning operation. *Trans. ASAE* 43 (6), 1393–1400.
- Holt, G.A., Laird, J.W., 2002. COBY Products and a Process for Their Manufacture, 2002. U.S. Patent No. 6,383,548.
- Holt, G.A., Richardson, C.R., Nunery, G.A., Wilson, K.F., Bramble, T.C., Rea, L.D., Wedegaertner, T.C., 2003a. Performance of growing heifers fed diets containing cotton gin byproducts extruded by the coby process. *The Prof. Anim. Sci.* 19, 404–409.
- Holt, G.A., Simonton, J., Beruvides, M.G., Canto, A.M., 2003b. Engineering economic analysis of a cotton by-product fuel pellet operation. *J. Cotton Sci.* 7 (4), 205–216.
- Holt, G.A., Wilkinson, H., Lee, E., 2003c. The COBY process: new value-added uses of cotton byproducts for the green industry. *Proc. Beltwide Cotton Conf.*, pp. 2543–2548.
- Holt, G.A., Buser, M.D., Pelletier, M.G., Harmel, R.D., Potter, K.N., Lee, E., 2004a. The COBY process: erosion control study results. *Proc. Beltwide Cotton Conf.*, pp. 994–1000.
- Holt, G.A., Simonton, J.L., Beruvides, M.G., Canto, A.M., 2004b. Utilization of cotton gin by-products for the manufacturing of fuel pellets: an economic perspective. *Appl. Eng. Ag.* 20 (4), 423–430.
- Jenkins, B.M., 1993. *Properties of Biomass. Biomass Energy Fundamentals Volume 2: appendices*. Prepared for Electric Power Research Institute, Palo Alto, CA.
- Karpiscak, M.M., Rawles, R.L., Foster, K.E., 1982. Densification of cotton gin trash into fireplace fuel. In: *Proceedings of the Symposium Cotton Gin Trash Utilization Alternatives*, National Science Foundation, pp. 87–99.
- Kolarik, W.J., Lalor, W.F., Smith, M.L., 1978. Cotton Gin Waste in Texas. Cotton Gin and Oil Mill Press, pp. 14–16.
- Kolarik, W.J., Smith, M.L., 1978. Economic Evaluation of South Plains (Texas) Ginning Waste as a Raw Material in the Production of Roofing Felt. Report prepared for Cotton Incorporated, Agreement No. 78-383.
- Lacewell, R.D., Moore, D.S., Parnell Jr., C.B., 1982. Pelletizing cotton gin trash for energy. In: *Proceedings of the Symposium Cotton Gin Trash Utilization Alternatives*, National Science Foundation, pp. 141–161.
- LePori, W.A., Carney, D.B., Parnell Jr., C.B., Lacewell, R.D., 1982. Energy from cotton gin trash. In: *Proceedings of the Symposium Cotton Gin Trash Utilization Alternatives*, National Science Foundation, pp. 101–117.
- Moran, J.C., Granada, E., Porteiro, J., Miguez, J.L., 2004. Experimental modeling of a pilot lignocellulosic pellets stove plant. *Biomass Bioenergy* 27, 577–583.

- Nakayama, F.S., Holt, G.A., Coffelt, T.A., Vinyard, S.H., Faber, A.L., 2003. Pellet fuel from guayule plant materials. Association for the Advancement of Industrial Crops, Annual Meeting, October 12–15. Portland, OR, Abst., p. 62.
- Parnell Jr., C.B., LePori, W.A., Capareda, S.C., 1991. Converting cotton gin trash into usable energy-technical and economical considerations. *Proc. Beltwide Cotton Conf.* 2, 969–972.
- PFI, 2005. Pellet Fuels Institute website. <http://www.pelletheat.org/3/industry/index.html>.
- Poore, M.H., Rogers, G., 1995. Feeding whole cottonseed and other cotton by-products to beef cattle. *Veterinary-Medicine* 90 (11), 1077–1087.
- SAS Help, 2003. PROC GLM Means Statement, SAS Software: SAS Information. Release 8.02, SAS Institute, Cary, NC.
- Shumack, R.L., Eakes, D.J., Gilliam, C.H., Donald, J.O., 1991. Using gin trash in composted soil ingredients. *Proc. Beltwide Cotton Conf.* 1, 498–499.
- Tejada, M., Dobao, M.M., Benitez, C., Gonzalez, J.L., 2001. Study of composting of cotton residues. *Biores. Tech.* 79, 199–202.
- Tejada, M., Gonzalez, J.L., 2003. Effects of the application of a compost originating from crushed cotton gin residues on wheat yield under dryland conditions. *Eur. J. Agron.* 19, 357–368.
- Thomasson, J.A., 1990. A review of cotton gin trash disposal and utilization. *Proc. Beltwide Cotton Conf.*, pp. 689–705.
- Truhett, C., 1994. Developing markets for composted gin waste. *Proc. Beltwide Cotton Conf.* 1, 609.
- U.S. EPA, 1997a. Code of Federal Regulations: Title 40. Part 60, Appendix A, pp. 702–708.
- U.S. EPA, 1997b. Code of Federal Regulations: Title 40. Part 60, Appendix A, pp. 662–672.
- White, D.H., Coates, W.E., Wolf, D., 1996. Conversion of cotton plant and cotton gin residues to fuels by the extruder-feeder liquification process. *Biores. Tech.* 56, 117–123.
- Young, K.B., Griffith, C., 1976. Economics of Using Gin Trash in Feedlot Rations, Texas High Plains. Texas Tech University, College of Agricultural Sciences, Publ. No. T-1-146.
- Zabaniotou, A.A., Roussos, A.I., Koroneous, C.J., 2000. A laboratory study of cotton gin waste pyrolysis. *J. Anal. Appl. Pyrol.* 56, 47–59.